FROST HEAVE OF SALINE SOILS

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Theories of ice segregation and frost heave processes in saline soils are briefly examined and modified to explain observations made on clay and sand soils frozen under laboratory conditions. Seawater was observed to reduce the rate of frost heave by more than 50% for both soil types and to dramatically reduce the size of ice lenses. The effect of seawater is to cause the formation of a thick active freezing zone with many ice lens growth sites, each with its own brine concentration. Unbonded brine-rich soil zones between ice lenses are identified as potential zones of low shear strength.

An understanding of the frost-heave and ice-segregation behavior of soils that contain saline pore water is important to the development of offshore petroleum resources in the Beaufort Sea. Understanding the freezing behavior of saline soils is also important to the artificial ground freezing industry. Unfortunately, little is known of ice segregation processes in saline soils that would allow design for frost heave and for changes in physical and mechanical properties.

Mahar et al. (1982) reported a modified form of the Berggren equation to predict frost penetration in saline soils where little or no frost heave occurs. This is important for determining where potential failure planes may occur in artificial islands. If significant amounts of ice segregation and frost heave occur, however, this method may overpredict the depth of freezing. In addition, the potential failure plane may not be forced below the region of freezing as commonly assumed. Partially frozen brine-rich zones within frozen layers may occur and they must also be considered as potential failure zones. A good example of this type of problem was recently observed at a ground freezing site (Maishman, personal communication) where, after excavation, a brine-rich clay layer was observed to slough back to the freezing pipes. Inspection of the site showed that the soil between ice lenses had little ice bonding and thus provided little strength for supporting the excavation.

Inspection of borehole logs obtained by Osterkamp and Harrison (1979) on Reindeer Island in the Beaufort Sea reveals that the occurrence of ice and ice bonding is sporadic and unpredictable, even though temperatures were below the freezing point of seawater.

This paper presents the results of a series of laboratory freezing tests on two soil types saturated with seawater. The freezing behavior is compared with freezing tests on the same soil types saturated with distilled water. Finally, an explanation for the unique freezing behavior of saline soils is offered.

FREEZING PROCESSES IN SALINE SOILS

The freezing of soils that contain saline pore water solutions is a complex process, due to the soluble salts in the pore water fluid. The effects of salts on freezing behavior extend well beyond simply lowering the freezing point. Salts are excluded from growing ice crystals and are concentrated in the adjacent pore fluids, so that ice segregation temperatures are lowered and additional sites for ice nucleation form at or near the original ice segregation temperature.

Hallet (1978) suggested that ice tentacles reach out from a morphologically complicated interface. Domains of solute-rich solutions can become isolated from the unfrozen pore-water solutions and eventually become trapped in solidly ice-bonded material. He suggested that significant solute partitioning will accompany frost penetration in frozen ground, with lower bulk concentrations occurring in ice-bonded layers, and increased concentrations of salt occurring in unfrozen soils beneath a growing ice lens. He further stated that constitutional supercooling in soils will lead to a situation where ice will nucleate and grow in a zone ahead of and separate from the freezing front.

Sheeran and Yong (1975) suggested that ice growth in pores that contain salt solutions requires progressively reduced temperatures because the increased salt concentration due to brine exclusion lowers the freezing temperature of the remaining adjacent pore water. Only partial freezing occurs at the freezing front. Substantial phase change may occur up to a meter behind the frost front as cooling continues, depending on the magnitude of the thermal gradient.

Mahar et al. (1982) concluded that the freezing front progressing through saline saturated soil is characterized by a transition zone of partially frozen soil grading from isolated ice crystals to ice-bonded soil. Continued ice growth requires progressively reduced temperatures. Because of the irregular shape of soil grain boundaries and the complex heat transfer pattern in a pore space, isolated brine pockets develop that may not freeze.

The situation in freezing saline soils is somewhat analogous to the frozen fringe concepts of Miller (1978) and Konrad and Morgenstern (1981). The hydraulic conductivity of the frozen fringe controls the availability of water to growing ice lenses. In the case of saline soils, however, the frozen fringe can be very thick, and ice accumulation probably occurs throughout the zone.

TABLE 1 Properties of the test materials.

Material	Percent finer than 2.0 mm	0.42 mm	0.074 mm	0.02 mm	0.005 mm	0.001 mm	Uniformity coefficient	Liquid limit %	Plastic limit %	Unified soil class
Morin clay	100	100	99	84	52	26	16	30	21	CL
Dartmouth sand	96	68	40	18	6	1	29	25	25	SM

TABLE 2 Specimen properties.

Material	Compaction properties: Water content %	Dry density Mg/m^3	Void ratio	Saturated water content %
Morin clay	9	1.51	0.84	30
Dartmouth sand	10	1.72	0.56	21

EXPERIMENTAL STUDIES

Two frost-susceptible soils, Dartmouth sand and Morin clay, were selected for this study. Dartmouth sand is a well-graded granular material containing numerous fines. The Morin clay material is classified as a clay of low plasticity. The properties of each of these materials are given in Table 1.

Replicate specimens of both of these materials were prepared using distilled water and seawater solutions. The samples were compacted in layers in 150-mm-diameter multiring Plexiglas cylinders, 150 mm high, lined with rubber membranes. The specimen properties are shown in Table 2. After compaction, the test specimens were saturated with the appropriate water solution under vacuum.

Calibrated thermocouples were inserted at 25-mm intervals through the sides of the rings to monitor the progress of freezing. The appropriate distilled water or seawater solution was made freely available through a porous stone at the base of the sample. Cooling plates connected to refrigerated circulating baths were placed at the top and bottom of each sample, and the entire assembly was placed in an insulated box in a cold room with a 0°C ambient temperature. A small surcharge of 24 kPa was placed on top of each sample.

Freezing was accomplished in three stages: (I) constantly decreasing boundary temperatures; (II) fixed boundary temperatures; and (III) rapidly decreasing boundary temperatures.

During Stage I, a temperature gradient of approximately 0.025°C/mm was propagated downward through the test specimens at a frost penetration rate of approximately 1.5 mm/hr until the zone of freezing was within the middle 50 mm of the test specimen. During Stage II, the boundary temperatures were held fixed, imposing the same temperature gradient for at least 100 hr. Finally, in Stage III, the samples were frozen rapidly to the bottom. The purpose of this freezing procedure was to establish frost heave and brine exclusion characteristics under a constant rate of frost penetration, then to force the growth of ice lenses and the exclusion of salts, and finally to trap the excluded brine for further analysis.

PRESENTATION AND DISCUSSION OF RESULTS

Four freezing tests were conducted on each of the clay and sand materials, two each for the distilled water and seawater solutions. Typical results for each of the soils and pore water solutions are illustrated in Figures 1 through 4. Individual test results are discussed below.

Morin Clay

The Morin clay samples saturated with distilled water heaved rapidly at nearly 12.5 mm/day during Stage I (Figure 1). The frost-heave rate during Stage II of freezing gradually slowed to approximately 2 mm/day. Many small ice lenses developed during Stage I (Figure 1), and a very large ice lens, nearly 50 mm thick, developed during Stage II. The growth of the ice lens during Stage II was shut off by the depletion of the water content in the unfrozen zone below to the plastic limit w_p.

The frost-heave rate for the Morin clay saturated with seawater was 60% lower than that for the distilled water (Figure 2). During Stage I of freezing, the heave rate for the seawater was approximately 4.5 mm/day; it fell below 1 mm/day during Stage II. No large ice lenses were observed to form during either of these stages. Water contents were limited to 50% in the ice-lensed zone (vs. nearly 400% for the distilled water case), and to 35% in the zone frozen rapidly during Stage III. Salinities were considerably partitioned by the freezing process, being reduced to as little as two-thirds of the original value (34.6‰) in the ice-lensed zone and increased by nearly 25% in the zone beneath the active ice lens growth. It should be noted that the salinities were determined for 15-mm-thick slices and represent bulk salinities of the soil, ice, and unfrozen water system. Salinity partitioning within smaller elements of each slice was not determined.

Dartmouth Sand

The Dartmouth sand froze with a 50-mm zone of fine- to medium-size ice lenses (Figure 3), most of which formed during Stage I of freezing. The fixed boundary conditions of Stage II could not induce the growth of large ice lenses. The frost-heave rate during Stage I was approximately 8 mm/day, but it fell to nearly 2 mm/day during Stage II.

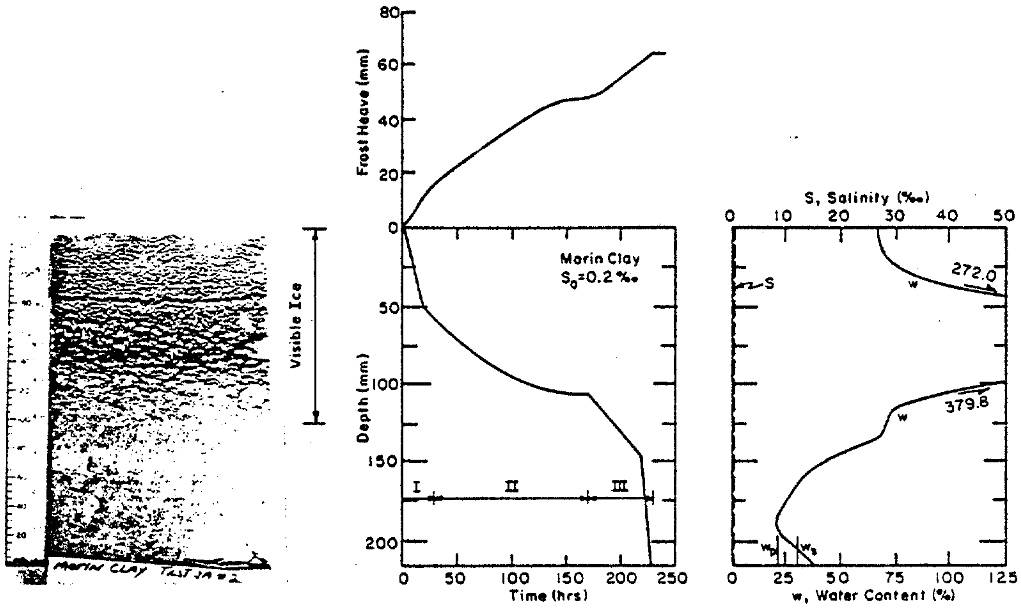

FIGURE 1 Freezing test results for Morin clay saturated with distilled water. Natural salinity S_0 is 0.2%. Plastic limit water content w_p and saturation water content w_s are shown for comparison.

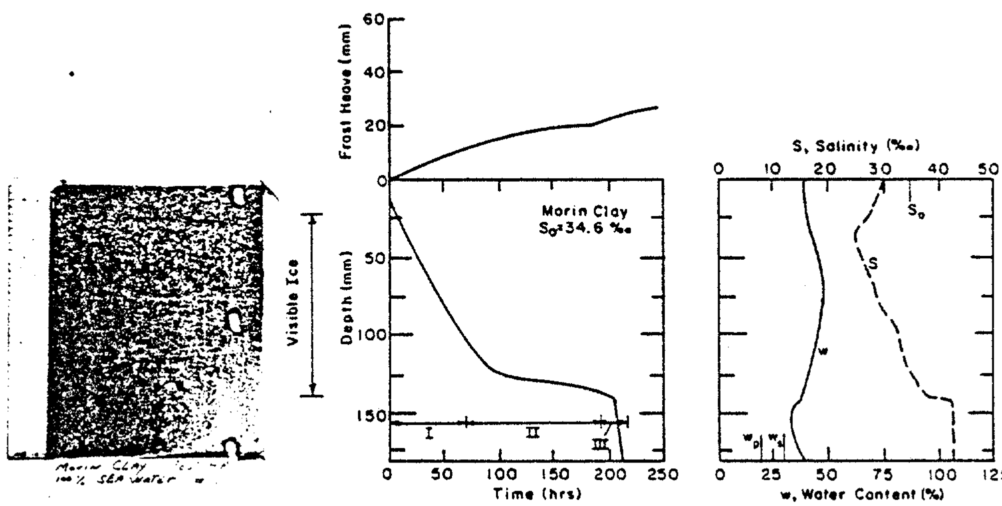

FIGURE 2 Freezing test results for Morin clay saturated with seawater. Initial salinity S_0 is 34.6%.

Water contents in the visible ice region were as much as 60%, whereas in the zone rapidly frozen during Stage III they were reduced to less than the original saturated water content of 21%.

Addition of the seawater solution to the Dartmouth sand markedly reduced the frost-heave rate and changed the ice segregation characteristics as it did with the Morin clay. The heave rate during Stage I was less than 3.5 mm/day and it fell to less than 0.5 mm/day during Stage I (Figure 4). Little visible ice was evident. The maximum water content was 30%, which indicates that some ice segregation occurred (the initial saturation water content was 21%). The water content in the rapidly frozen zone formed during Stage III was only slightly above the initial water content, which indicates that little ice segregation occurred there.

The salinity profile (Figure 4) is partitioned to approximately 85% of the original salinity (S_0 = 35.7%) in the upper portions frozen during Stage I and the early part of Stage II, and increases to 120% of S_0 in the region frozen during Stage III.

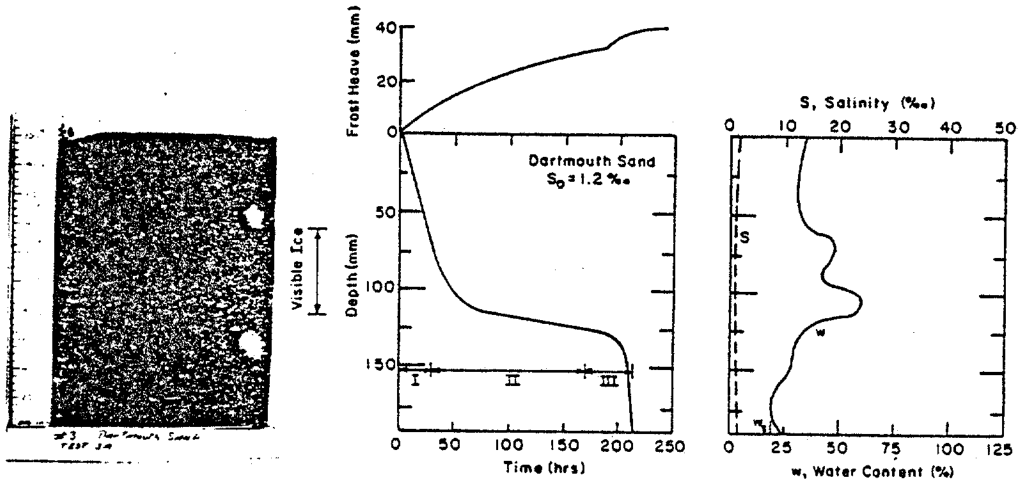

FIGURE 3 Freezing test results for Dartmouth sand prepared with distilled water. Natural salinity S_o is 1.2%.

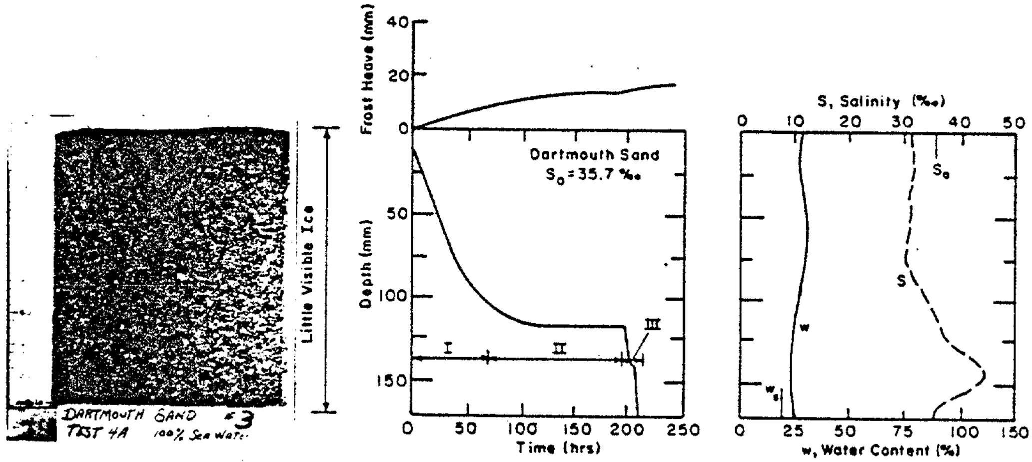

FIGURE 4 Freezing test results for Dartmouth sand prepared with seawater. Initial salinity S_o is 35.7%.

CONCEPTUAL CHARACTERIZATION OF THE EFFECTS OF SALTS ON FROST HEAVE

A few explanations for the effects of salts on frost heave in soil materials were briefly reviewed earlier in this paper. A refinement of these explanations is suggested to account for the reduced ice segregation potential of saline soils and to explain the apparent simultaneous formation of several ice lenses witnessed by Mahar et al. (1982) and shown in the recent freezing tests.

As Hallet (1978) suggested, the solute concentration in saline soils is partitioned by freezing, with solutes being rejected to the surface of the growing ice lens. A schematic diagram of the freezing process is shown in Figure 5. Ice first nucleates when the temperature of the saline pore water T_w falls below the initial equilibrium freezing temperature T^o_{eq} (Figure 5a). As T_w is lowered with time, the ice lens grows, excluding salt into the unfrozen zone below while trapping some brine within the ice.

A second ice lens formation site develops (Figure 5b) when T_w falls below the equilibrium freezing temperature beneath the brine concentration. Ice will continue to grow at the first site at progressively reduced temperatures, concentrating salts in the unfrozen soil layer between the two ice growth sites until the hydraulic conductivity of this layer is insufficient to meet the demand. As T_w continues to be lowered, a second brine concentration forms and a third ice growth site develops below it (Figure 5c). Continuation of this process will result in the growth of many ice lenses concurrently. Growth of the uppermost active ice lens will stop when water is no longer available.

The average equilibrium freezing temperature for all the equivalent moisture within the frozen

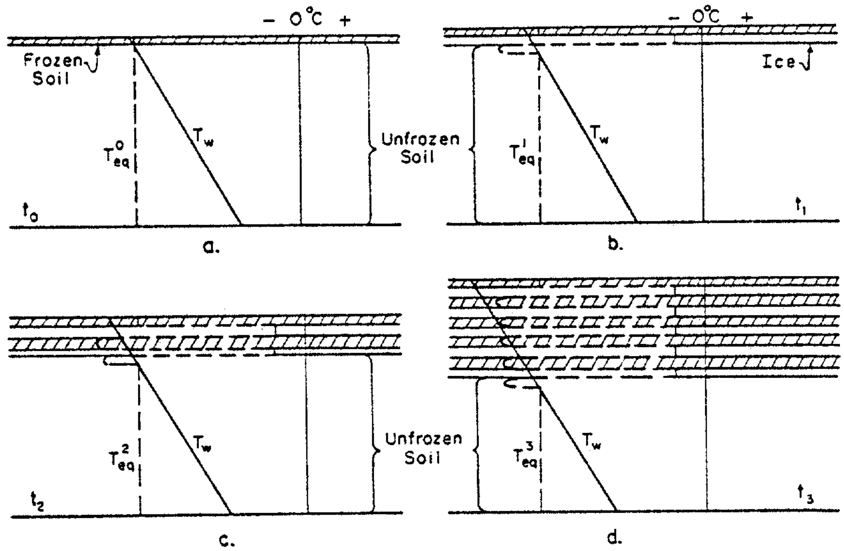

FIGURE 5 Schematic diagram of ice segregation process in saline soils. (a) At time zero (t_o), the pore water temperature profile is T_w and a thin soil layer has frozen; (b) at time t_1, an ice lens is growing and a freezing point depression bulb has formed beneath it due to the exclusion of salts. The segregation freezing temperature at the first ice lens growth site decreases because of the brine concentration, and a second ice nucleation site forms; (c) at time t_2, a third ice nucleation site has formed below the freezing point depression bulb formed by the second ice lens; (d) the process continues at time t_3, with many ice lens growth sites. Ice lens growth at the original nucleation site is shut off by reduced hydraulic conductivity.

zone is higher than the initial condition T^o_{eq} because of the net exclusion of brine. The equilibrium freezing temperature within the soil elements is lower than T^o_{eq} because of brine concentrations in the unfrozen water.

The growth of large ice lenses is restricted by this process because the many small ice lenses and entrapped soil layers lower the hydraulic conductivity within the active freezing zone. Furthermore, the increasing concentration of salts near each ice lens growth site requires progressively lower temperatures to continue growth, whereas progressively lower temperatures reduce the hydraulic conductivity. The flow of water to the uppermost growing ice lens is thus shut off before the lens can develop significant thickness.

FURTHER DISCUSSION OF RESULTS

The water content profiles in Figures 1 through 4 give some evidence of the reduced hydraulic conductivity of the freezing zone in saline soils. For Morin clay prepared with distilled water (Figure 1), the water content in the soil below the zone of high ice segregation has been reduced to the plastic limit water content, which is the practical limit to which a soil can be desiccated by the freezing process (Chamberlain 1981). For the case of the saline Morin clay (Figure 2), the water content in the soil beneath the active ice segregation zone actually increased over the initial saturated (w_s) value during the passing of the freezing front. This indicates that there is a tendency to desiccate the soil elements within the high suction zone of freezing in saline clay soils and to reduce the hydraulic conductivity there, whereas in the clay soil prepared with distilled water the highly desiccated zone lies below the active freezing front.

IMPLICATIONS

Under natural freezing conditions with very small temperature changes with depth, such as within islands in the Beaufort Sea, thick zones of active freezing can occur with alternating zones of ice-bonded and salt-enriched unbonded soils.

From an engineering design point of view, the reduced frost-heave susceptibility of saline soils is a positive factor. However, if the design of an artificial island is predicated on the development of the ice-bonded strength of the fill material, unfrozen zones with brine concentrations may cause weak zones to form above the freezing front.

Under artificial freezing conditions for construction purposes, unfrozen zones of brine-enriched soil can also occur, particularly in clay soils. These unfrozen zones can cause failure of a freeze-wall, even if they are only a few millimeters thick.

CONCLUSIONS

The frost-heave susceptibility of sand and clay soils is significantly reduced by saline pore water. Salts also dramatically reduce the ice lens size and decrease the segregation water content.

The effect of saline seawater on frost heave and ice segregation can be explained in terms of a thick active freezing zone with many ice lens growth sites, each with its own brine concentration. The thick active freezing zone reduces the hydraulic conductivity, and thus the rate of frost heave.

The brine concentrations can cause zones of unbonded soil to occur within an ice-bonded material. These zones of brine concentration can cause planes of low shear strength to occur in frozen structures. These potential failure planes must be considered by engineers designing artificial islands to resist ice forces or ground-freezing projects to stabilize excavation sites.

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